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RECENT DEVELOPMENTS IN HIGH POWER HIGH BRIGHTNESS DOUBLE BUNCH SELF-SEEDING AT LCLS-II

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Abstract

We discuss the power and spectral characteristics of an X-ray FEL, LCLS-II, operating in a double bunch self-seeding scheme (DBFEL). We show that it can reach very high power levels in the photon energy range of 4-8 keV. We discuss the system implementation on LCLS-II, including the design of a four-bounce crystal monochromator, and linac wakefields effects. Finally, we offer multiple applications of the DBFEL for high-field QED, AMO physics and single particle imaging.

INTRODUCTION

Two- and multi-bunch copper RF (CuRF) linac operation capability expands the capabilities of the existing X-ray free electron lasers (XFELs) [1–5]. For example, we have previously shown that it greatly helps in producing very high power and nearly transform limited XFEL pulses [6].

The idea of double bunch FEL (DBFEL) is similar to fresh slice self-seeding scheme, except in the former case the entire first bunch is used for SASE radiation generation, and the entire second bunch is seeded and used for lasing. DBFEL requires a number of critical components to be added to a nominal XFEL beamline. First, two electron bunches must be produced in a photoinjector. In practice this is done by splitting the existing UV laser pulse into two pulses with a variable delay, or by using two individual lasers.

Second critical component is the four crystal Bragg monochromator, which provides narrow bandwidth radiation for seeding, and also delays the radiation by the amount of bunch separation. For practical implementation of the monochromator, it must be compact to fit in the existing HXRSS chicane space, therefore imposing a constraint on the double bunch delay time. We have discussed the geometry of the monochromator in [7].

Both bunches must be properly controlled in the linac and undulators, to alleviate wakefield effects, and to put the second bunch initially off-axis in the SASE section, and return it back on-axis in the amplifier section. This will be done by using an ultra-fast transmission line kicker with the rise time of 0.5 ns. The kicker parameters and conceptual design was presented in [7].

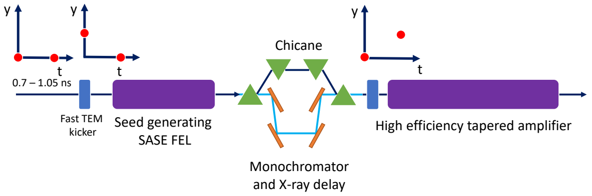

Figure 1: DBFEL schematics: two bunches with 0.7 - 1.05 ns separation are used to generate a high power seed on the second cold bunch at the entrance of the tapered amplifier.

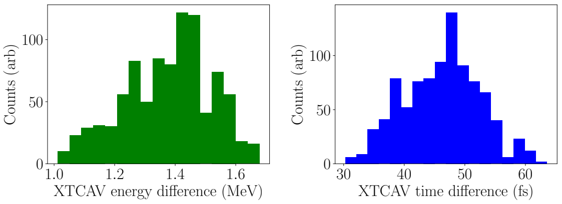

Figure 2: Energy and time-separation jitter for 50 ns double bunch separation. The RMS values are 0.3 MeV and 6.2 fs for energy and time jitter accordingly.

Currently, we are considering a DBFEL setup at LCLS-II hard X-ray (HXR) undulator shown in Fig. 1. The length of the SASE section is 7 undulators and the amplifier section consists of 25 undulators. To minimize detrimental effects of the long range wakefields in the CuRF linac, we consider 0.7 ns or two-bucket double bunch separation.

DOUBLE BUNCH JITTER MEASUREMENTS

LCLS CuRF linac has repeatedly demonstrated multi-bunch capability for various bunch separations [8–11]. An important parameter for a successful DBFEL operation is the double bunch separation jitter. For the first round of measurements, we generated two bunches at about 50 ns or 143 RF-buckets separation, and collected about 1000 XTCAV images. We then deconvolved first and second bunch from the image, to determine their individual center of mass position, and the RMS jitter in time and energy separation.

We found RMS energy jitter to be 0.3 MeV and RMS time jitter to be 6.2 fs respectively; see Fig. 2. The values are updated with more data from previously reported cases. We expect the jitter to be significantly smaller for shorter separations. A detailed study is planned shortly after LCLS-II commissioning. Double- and multi-bunch jitter are also critically important parameters for the successful operation of cavity based XFEL, such as the proposed regenerative amplifier FEL (RAFEL) at LCLS-II [5].

SIMULATIONS OF DBFEL PERFORMANCE

We note, that in our initial studies we used a quasi flat-top current distribution, previously considered and experimen-

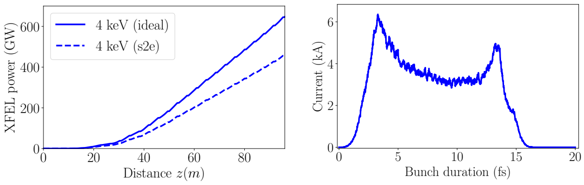

Figure 3: Simulation of DBFEL performance at 4 keV photon energy (left) for the case of ideal flat-top current distribution and start-to-end current distribution (right), generated by ELEGANT.

tally demonstrated at LCLS [12]. To further investigate DBFEL performance, we generated a particle distribution using the well known codes IMPACT-T and ELEGANT, including wakefield effects in the S-band accelerating structures and compression chicanes in our simulation. We then considered two identical particle distributions to generate the SASE field and perform self-seeding. The FEL simulations were performed in [13] running in time-dependent mode using the tapering technique outlined in [6]. The start-to-end simulation is currently an ongoing effort and will continue to be refined in the future. We considered conservative CuRF 60 pC beam parameters, with 0.4 μm normalized transverse emittance and 2 MeV energy spread, that have been previously experimentally demonstrated at LCLS [12]. In case of ideal flat-top beam current with aforementioned parameters, one can obtain up to 650 GW at 4 keV photon energy. We estimate, with detailed machine optimization, this value is feasible and increases the designed LCLS-II HXR 4 keV X-rays peak power by factor of 3 or 4 as shown in Fig. 3.

For the case of 8 keV photons, we have previously considered a longer SASE section of 9 undulators [6]. We demonstrated it can significantly increase the XFEL peak power at 8 keV, up to 400 GW, while only slightly decreasing it at 4 keV. With the SASE section of 8 undulators, this value becomes about 200 GW. However, increasing the length of the SASE section may be impractical and interfere with other LCLS-II projects. Ultimately, the experimental gain length of 8 keV photons is the defining constraint. Therefore, we will address DBFEL performance at 8 keV with the existing SASE section length of 7 undulators. In this case, DBFEL 8 keV X-ray photon power is limited by the value of the seed power and the length of the amplifier section, so the total peak XFEL power is about 140 GW.

At higher photon energy, e.g. up to 12 keV, it is even more challenging to have a large peak power. However, using a different undulator design, as discussed in the next Section, can significantly improve the performance.

DBFEL WITH AGU

Tthe XFEL power extracted from the electron beam in the amplifier section can be drastically increased by using superconducting planar/helical undulators with a distributed trasnverse focusing to minimize the beam area. We refer to it as Advanced Gradient Undulator (AGU) and investigated it in detail in [14]. Our simulations indicate that DBFEL working with AGU undulator of about 100 m long with parameters similar to [14], can produce multi-terawatt 12 keV photon pulses, as shown in Fig. 4. We note that similar conclusions have been drawn in a normal conducting undulator with a very strong focusing FODO lattice [15].

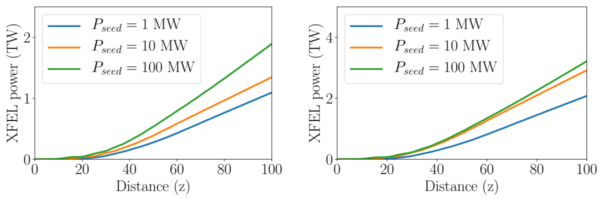

Figure 4: Tapered 100 m planar AGU (left) and helical AGU (right) XFEL peak power at 12 keV with different seed power values.

SUMMARY

We have presented an update on recent developments of DBFEL concept at LCLS-II. In particular, we discussed the cases of very high XFEL power for 4 keV photons and possible improvements in peak power for 8 keV photons. We calculated RMS time and energy separation jitter for the existing double bunch dataset. A detailed study of different CuRF multi-bunch modes is scheduled in the near future. We also show that by adding stronger focusing in the undulator lattice, for instance using an AGU undulator, in DBFEL, one can significantly increase the XFEL power.

DBFEL at LCLS-II may open the avenue for many new high-field scientific experiments, assuming the existing KB-mirrors are upgraded to focus down to tens of nm scale. In addition, high peak power XFEL pulse from DBFEL may be back-reflected and collided with a third electron bunch or an XFEL pulse, forming a electron-gamma or gamma-gamma collider. High power HXR pulses are also required for single particle imaging experiments.

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REFERENCES

[1] E. L. Saldin, E. A. Schneidmiller, Yu. V. Shvyd'ko, and M. V. Yurkov, "X-ray FEL with a meV bandwidth", *AIP Conference Proceedings*, vol. 581, pp. 153-161, Sep. 2001.

[2] G. Geloni, V. Kocharyan, and E. Saldin, "Scheme for generation of highly monochromatic X-rays from a baseline XFEL undulator", *arXiv, physics.acc-ph:1003.2548*, Mar. 2010.

[3] G. Geloni, V. Kocharyan, and E. Saldin, "Extension of self-seeding scheme with single crystal monochromator to lower energy < 5 keV as a way to generate multi-TW scale pulses

at the European XFEL", *arXiv, physics.acc-ph:1207.1981*, Jul. 2012.

[4] Y. Ding, Z. Huang, and R. D. Ruth, "Two-bunch self-seeding for narrow-bandwidth hard x-ray free-electron lasers", *Phys. Rev. Spec. Top. Accel. Beams*, vol 13, p. 060703, Jun. 2010.

[5] G. Marcus, *et al.*, "Cavity-based free-electron laser research and development: a joint Argonne National Laboratory and SLAC National Laboratory collaboration", in *Proc. of FEL19*, Hamburg, Germany, Aug. 2019, paper TUPRB086.

[6] A. Halavanau, F.-J. Decker, C. Emma, J. Sheppard, and C. Pellegrini, "Very high brightness and power LCLS-II hard X-ray pulses", *J. Synchrotron Radiat.*, vol. 26, pp. 635-646, 2019.

[7] A. Halavanau, *et al.*, "Progress in High Power High Brightness Double Bunch Self-seeding", In *Proc. of FEL19*, Hamburg, Germany, Aug. 2019, paper TUP092.

[8] F.-J. Decker *et al.*, "A demonstration of multi-bunch operation in the LCLS", in *Proc. of FEL2010*, Malmoe, Sweden, Jan. 2010, pp. 467-470.

[9] F.-J. Decker, *et al.*, "Two Bunches with ns-Separation with LCLS", in *Proc. of FEL 2015*, Daejeon, Korea, Dec. 2015, paper WEP023.

[10] F.-J. Decker, K. Bane, W. Colocho, A. Lutman, and J. Sheppard, "Recent Developments and Plans for Two Bunch Operation with up to 1 us Separation at LCLS", in *Proc. of FEL2017*, Santa Fe, NM, USA, Aug. 2018, paper TUP023.

[11] F.-J. Decker, W. Colocho, S. Glenzer, A. A. Lutman, A. Miahnahri, D. Ratner, J. Sheppard, and S. Vetter, "Four X-ray Pulses within 10 ns at LCLS", in *Proc. of IPAC2019*, Melbourne, Australia, May 2019, paper TUPRB086.

[12] Y. Ding, *et al.*, "Start-to-End Simulations of the LCLS Accelerator and FEL Performance at Very Low Charge", in *Proc. of PAC09*, Vancouver, Canada, May 2009. paper WE5RFP040.

[13] S. Reiche, "GENESIS 1.3: a fully 3D time-dependent FEL simulation code", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 429, pp. 243-248, 1999.

[14] C. Emma, K. Fang, J. Wu, and C. Pellegrini, "High efficiency, multiterawatt x-ray free electron lasers", *Phys. Rev. Accel. Beams*, vol 19, p. 020705, 2016.

[15] H. P. Freund and P. J. M. van der Slot, "Studies of a terawatt x-ray free-electron laser", *New J. Phys.*, vol. 20, p. 073017, 2018.